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SYSTEM ISSUES RELATED TO SATELLITE COMMUNICATIONS IN A NUCLEAR ENVIRONMENT

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ABSTRACT

Nuclear induced signal scintillation effects are of great importance in design and deployment of military satellite systems that must provide survivable and enduring communications service. The induced scintillation will result in Rayleigh signal fading with limited signal decorrelation time and coherent bandwidth of the transmission channel as well as reduced signal power due to terminal antenna scattering loss.

In this environment the coherent bandwidth and signal decorrelation time are most important design parameters for modulation subsystem design. The antenna scattering loss is important for link power budgets and satellite network loading.

1. BACKGROUND

A high altitude nuclear detonation emits atomic particles and high energy photons, x-rays and γ-rays, that cause strong ionization of the gas in atmosphere and ionosphere. At lower altitudes the gas pressure is sufficiently high to cause very rapid recombining and annihilation of the charged particles while in the ionosphere, at the altitudes of about 100 to 1000 Km, the ionization will persist for substantial periods of time and affect signal propagation from minutes to hours and even days.

A hostile adversary may therefore elect to greatly increase the number of electrons and charged particles (ions) in the ionosphere to such a degree that it will cause multipath scattering effects of satellite communications signals passing through it. Strong ionization levels will affect and may even completely disrupt the satellite communications signal if this situation is not guarded against by proper design of the modulation subsystems and sufficient link power budget margins are used in engineering the communications networks.

The net result of the induced signal multipath propagation effects is that the signal power does not reach the terminal from the axial direction of the satellite but within an angular distribution about this "line of sight" direction. The angular distribution of signal components making up the composite signal has been determined to be approximately Gaussian [1]. That is, the probability density

$$p(\theta_x,\theta_y) = [1/(2\pi\sigma_x\sigma_y)]\exp[-(\theta_x/\sigma_x)^2/2-(\theta_y/\sigma_y)^2/2], \qquad 1\text{-}1$$

where θ_x, θ_y represent the angular deviation from the direct path and σ_x^2, σ_y^2

are the variances of the angular deviations. The probability density is normalized to unit "mass" which is very appropriate to a direct description of the forward scattering situation since there is no loss of average signal power through the scintillation medium but rather an angular re-distribution of the total signal power into components by the multipath scattering process. Simply, forward scattering implies that the transmitted signal from a satellite will "sooner or later" reach the earth but not necessary through the direct path. Therefore, we may determine the average signal power at an earth terminal by first determining the power level in the case of no signal scintillation (the normal case) and apply the angular distribution of (1-1) to this power and determine the signal power level received at the earth terminal when signal scintillation is present. Note, even though we have referred to a satellite downlink in developing the rationale for the probabilistic description of the nuclear induced signal scintillation channel, it applies equally well to an uplink signal by the virtue of the general law of transmission reciprocity between transmit and receive terminals.

The angular distribution of signal components from the scintillation medium will generally not be rotationally symmetric. That is, the variances σ_x^2, σ_y^2 may not be equal. It is due to the influence of the earth's magnetic field on the moving charged particles which cause them "gyrate" about the magnetic field lines. Thus, the scattering effect will be accentuated in the direction along these lines and less so perpendicular to them. The x and y axes in (1-1) are chosen in such a way that they line up with the major and minor axes of the angular signal distribution. From theoretical considerations the two variances are related to the maximum medium angular scattering variance σ_θ^2 as

$$\sigma_x^2 = \sigma_\theta^2/K(\Phi), \qquad \sigma_y^2 = \sigma_\theta^2/K^3(\Phi), \tag{1-2}$$

where $K^2(\Phi) = \cos^2(\Phi)+225\sin^2(\Phi) = 1+224\sin^2(\Phi)$, and thus

$$\sigma_y^2 = \sigma_x^2/K^2(\Phi), \tag{1-3}$$

where Φ is the signal penetration angle through the scintillation medium relative to the magnetic field. [The angle $\Phi = 0$ if the propagation path is parallel to the magnetic field lines.] As $1 \leq K(\Phi) < 15$ with $K(\Phi) = 1$ for $\Phi = 0$, we have in this case $\sigma_y^2 = \sigma_x^2 = \sigma_\theta^2$ and a symmetric angular scattering distribution. This case is almost possible for a terminal located due north or south of a geosynchronous satellite. For a terminal at the equator the penetration angle $\Phi = \pi/2$ (90 degrees) and we have the most nonsymmetric case with $\sigma_y^2 = \sigma_x^2/225$ and $\sigma_x^2 = \sigma_\theta^2/15$, which shows that the angular scattering dispersion is strongly reduced, by a factor of 15, from the maximum medium angular scattering in the scintillating volume.

2. RECEIVED SIGNAL FADE CHARACTERISTICS

There are several important factors to consider for satellite communications network design and link power budget determination to achieve the required communications performance under nuclear stressed situations. Specifically, the effects of Rayleigh signal fading, signal decorrelation time, channel coherent bandwidth and terminal antenna scattering loss will be considered.

The well developed multipath situation caused by nuclear induced signal scintillation implies that both the inphase [$\sqrt{Sx(t)}$] and quadrature phase [$\sqrt{Sy(t)}$] components of a signal will be uncorrelated Gaussian distributed random processes with zero mean and equal variance. This situation is referred to as Rayleigh fading which is alternatively characterized by a uniform

phase distribution and an exponential received power probability density

$$p(S(t)|S) = (1/S)\exp[-S(t)/S], \qquad 2\text{-}1$$

where $S(t) = S[x^2(t)+y^2(t)]$ is the instantaneous received power level and S denotes the average received signal power level over time. [Generally, the amplitude probability density $p(a|S) = (2a/S)\exp(-a^2/S)$ is referred to as the Rayleigh distribution which is equivalent to (2-1) with $a = \sqrt{S(t)}$.] In other words, instead of receiving the power level $S(t) = S$ at all times, the receive power level will be random at any given time instant governed by (2-1) and also varying with time. The time varying nature of the signal is fully defined statistically by the signal auto-correlation function which from the Gaussian nature of the angular scattering distribution as well as from the gain pattern of a circular antenna can be expressed as

$$\begin{aligned} R(\tau) &= E[x(t)x(t')]+E[y(t)y(t')] \\ &= \exp[-(\tau/\tau_0)^2], \qquad \tau = t-t', \end{aligned} \qquad 2\text{-}2$$

where also $E[x(t)x(t')] = E[y(t)y(t')]$. The parameter τ_0 is referred to as the decorrelation time and signifies that the signal values separated in time by $\tau = \tau_0$ for each of the quadrature components have a correlation equal to $\exp(-1)$. The Rayleigh fading situation is completely characterized by the average received power level, the exponential distribution of the instantaneous power and its covariance function.

Associated with a wide sense stationary process, whose autocorrelation function $R(\tau)$ only depends time displacement $\tau = t-t'$, is its power spectral density

$$S'(f) = \sqrt{\pi}\tau_0\exp[-(\pi\tau_0 f)^2] \qquad 2\text{-}3$$

obtained as the Fourier transform of (2-2), that physically represents the power spectral density of a received CW signal undergoing signal fading. If we define the signal bandwidth $B = 1/\sqrt{\pi}\tau_0$, then only $\mathrm{erf}(\pi\tau_0 B/2) = 0.79$ or about 80 percent of the power will be received within this bandwidth for a transmitted CW tone. This tone spectral spreading places a lower bound on the minimum detection bandwidth and the maximum modulation symbol period for which the received signal can be efficiently received.

The effects of angular scattering defined by σ_x^2 and σ_y^2, or alternatively by the corresponding equivalent "antenna gains" $G_{\sigma x} = 2/\sigma_x^2$ and $G_{\sigma y} = 2/\sigma_y^2$, adjusted by the influence of terminal antenna gain G_T, will affect the decorrelation, the channel coherent bandwidth and the antenna scattering loss. Specifically, we have the result for the signal decorrelation time

$$\tau_0 = 1/[(v_x/\ell_{ox})^2+(v_y/\ell_{oy})^2]^{1/2}, \qquad 2\text{-}4$$

where $\ell_{ox} = (\lambda/2\pi)\sqrt{G_x}$, $\ell_{oy} = (\lambda/2\pi)\sqrt{G_y}$ with $G_x = G_T+G_{\sigma x}$, $G_y = G_T+ G_{\sigma y}$, and where λ is the free space wavelength of the transmitted signal and v_x and v_y are the velocity components associated with the scattering medium motion relative to the terminal. Under strong nuclear scintillation conditions the terminal antenna gain G_T is typically much larger than $G_{\sigma x}$ and $G_{\sigma y}$ and then ℓ_{ox} and ℓ_{oy} approach their common minimum value $(\lambda/2\pi)\sqrt{G_T}$ that leads to the minimum decorrelation time $\tau_0 = (\lambda/2\pi v)\sqrt{G_T} = D/2v$, where $v = \sqrt{(v_x^2+v_y^2)}$ is the relative medium velocity. The last equality holds for a circular dish antenna having the gain $G_T = (\pi D/\lambda)^2$, where D is the antenna diameter. Thus, the minimum decorrelation time of the signal is governed by the antenna size and not by the antenna gain and angular scattering of the medium. In Table 2-1 the minimum signal decorrelation time is given for the various antenna gains.

Table 2-1 Minimum Signal Decorrelation Time in a Strong Nuclear Induced Scintillation Environment.

Terminal Antenna Gain	(Size at 7/8 GHz)	Relative Velocity, v: 100 m/s	300 m/s	1000 m/s
G_T = 62 dB	(60')	τ_o = 91.4 ms	= 30.5 ms	= 9.1 ms
= 58	(40')	= 61.0	= 20.3	= 6.1
= 52	(20')	= 30.5	= 10.2	= 3.1
= 44	(8')	= 12.2	= 4.1	= 1.2
= 35	(33")	= 4.2	= 1.4	= 0.4

The signal decorrelation time is directly related to the fade rate of the signal defined as the average number of times per second the signal power is less than a certain threshold level S_T. Specifically, the fade rate and the average fade duration [2]

$$R_f = (1/\tau_o)\sqrt{(2S_T/\pi S)}\exp(-S_T/S), \quad \text{Hz} \qquad 2\text{-}5$$
$$T_{fade} = \tau_o\sqrt{(\pi S/2S_T)}[\exp(S_T/S)-1], \quad \text{seconds.}$$

If we consider the threshold $S_T/S = 1/4$ -- that is, S_T is 6 dB below the average power level S -- the fade rate becomes $0.311/\tau_o$ and the average fade duration is $0.712\tau_o$. The maximum fade rate is $1/\tau_o\sqrt{(\pi e)} = 0.342/\tau_o$, which occurs for $S_T/S = 1/2$, or for a 3 dB margin threshold. We see that the fade rate is about 1/3 of $1/\tau_o$ and not equal to $1/\tau_o$ as commonly thought. Between the deep fades the signal is above this threshold and we can determine the average "strong" signal period

$$T_{signal} = 1/R_f - T_{fade} \qquad 2\text{-}6$$
$$= \tau_o\sqrt{(\pi S/2S_T)}, \quad \text{seconds,}$$

associated with the fading signal process. In Table 2-2 we have determined the fade rate and average duration for various signal decorrelation times.

In the technical development above we tacitly assumed single link fading, i.e., uplink or downlink fading. However, if we do experience simultaneous uplink and downlink fading and we use a transponder satellite, the combined signal variation will not constitute Rayleigh fading. It can be shown that the received signal has a uniform phase ditribution and a "Bessel" power probability density [2]

$$p(S(t)|S) = (2/S)K_o[2\sqrt{(S(t)/S)}], \qquad 2\text{-}7$$

where $K_o(\cdot)$ is the modified Bessel function of second kind and $S(t) = S[x_1^2(t)+y_1^2(t)][x_2^2(t)+y_2^2(t)]$ with subscripts 1 and 2 refering to the uplink and downlink, respectively. This distribution leads to Laplace distributed inphase and quadrature components

$$p[x(t)] = \exp[-2|x(t)|] \qquad 2\text{-}8$$
$$p[y(t)] = \exp[-2|y(t)|],$$

where $x(t)+iy(t) = [x_1(t)+iy_1(t)][x_2(t)+iy_2(t)]$ is the normalized received signal. [It should be noted that since the two quadrature components x(t) and y(t) are not Gaussian distributed, they are not uncorrelated and statistically independent even if the signal phase $\phi = \arg[x(t)+iy(t)]$ is still

Table 2-2 Signal Fade Rate, Average Fade Duration and Signal Period: Rayleigh Fading, Fade Threshold $S_T/S = -6$ dB.

Signal Decorrelation Time τ_o	Fade Rate R_f	Average Fade Duration T_{fade}	Average Signal Period T_{signal}
1 ms	311.0 Hz	0.7 ms	2.5 ms
10	31.1	7.1	25.1
100	3.1	71.2	251
1,000	0.3	712.0	2,510

uniformly distributed $[0,2\pi)$.] The signal correlation function

$$\begin{aligned} R(\tau) &= R_1(\tau)R_2(\tau) \\ &= \exp[-(\tau/\tau_o)^2], \qquad \tau = t-t', \end{aligned} \tag{2-9}$$

where $(1/\tau_o)^2 = (1/\tau_{o1})^2+(1/\tau_{o2})^2$ relates the resulting signal decorrelation time τ_o with those of the uplink (τ_{o1}) and downlink (τ_{o2}), respectively.

3. RECEIVED SIGNAL COHERENT BANDWIDTH

Closely associated with the decorrelation time of the signal is the coherent bandwidth (f_o) of the transmission channel. This performance parameter determines the maximum (approx.) bandwidth that allows for non distorted digital signal transmissions and is directly tied to the multi-path delay spread in the channel. The effective coherent bandwidth is also governed by σ_x^2 and σ_y^2 and the terminal antenna gain G_T, or equivalently $G_x = G_T+G_{\sigma x}$ and $G_y = G_T+ G_{\sigma y}$. From geomertic considerations [2], we have the result

$$f_o = (c/4\pi h)[(1/G_x^2+1/G_y^2)/2]^{1/2}, \qquad \text{Hz}, \tag{3-1}$$

where c denotes the speed of propagation and h is the effective height (distance) to the scattering volume from the terminal. For strong scintillation conditions both G_x and G_y approach G_T and $f_o = (c/4\pi h)G_T$. Thus the minimum coherent bandwidth is determined by the terminal antenna gain and the effective scattering volume height. This observation is most important from a systems engineering point of view; a satellite network with a certain minimum size of earth terminals can be ensured a significantly larger coherent bandwidth than that which the scintillation medium itself defines to a very small (omni directional) antenna. [Tha is, if we let G_T approach zero above]. In Table 3-1 the minimum coherent bandwidth has been determined for various size terminal antennas.

The important observation to be made is that the minimum signal decorrelation time and coherent bandwidth are lower bounded by the terminal antenna gain, the terminal-satelite geometry and the velocity of the scattering medium. The results are not dependent on the angular sattering variances which are strongly dependent on the nuclear senario. This implies that if the minimum decorrelation and coherent bandwidth results are used as design criteria for the modulation subsystem developments the resulting design will meet operational requirements for all nuclear senarios.

Again we have tacitly only considereed a single link. If we consider both uplink and downlink fading, the resultant channel coherent bandwidth f_o

Table 3-1 Minimum Signal Coherent Bandwidth in a Strong Nuclear Induced Scintillation Environment.

Terminal Antenna Gain	(Size at 7/8 GHz)	Effective Height, h 300 km	1000 km	3000 km
$G_T \approx 62$ dB	(60')	$f_o \approx 126$ MHz	$\approx$ 38 MHz	$\approx$ 13 MHz
$\approx$ 58	(40')	$\approx$ 50	$\approx$ 15	$\approx$ 5.0
$\approx$ 52	(20')	$\approx$ 13	$\approx$ 3.8	$\approx$ 1.3
$\approx$ 44	(8')	$\approx$ 2.0	$\approx$ 600 kHz	$\approx$ 200 kHz
$\approx$ 35	(33")	$\approx$ 250 kHz	$\approx$ 75	$\approx$ 25

is given by

$$(1/f_o)^2 = (1/f_{o1})^2+(1/f_{o2})^2 \quad 3\text{-}2$$

in terms of the uplink (f_{o1}) and downlink (f_{o2}) coherent bandwidths, respectively [2].

4. ANTENNA SCATTERING LOSS

Even if the antenna scattering loss does not affect the modulation subsystem design we will briefly mention its effect. The average receive power level is also affected by the angular scattering of the medium and the terminal gain as the limited beam width of an antenna will reject signal component with large scattering angles. Specifically, the net received (average) signal power level

$$S = S_o/[(1+G_T/G_{\sigma x})(1+G_T/G_{\sigma y})]^{1/2}, \quad 4\text{-}1$$

where S_o is the received power level before the nuclear event and as before $G_{\sigma x} = 2/\sigma_x^2$ and $G_{\sigma y} = 2/\sigma_y^2$ are the equivalent terminal gains associated with the angular scattering process [2]. Thus, the terminal antenna scattering loss

$$\begin{aligned} L_s &= 10\log(S_o/S) \quad \text{dB} \\ &= 5\log(1+G_T/G_{\sigma x})+5\log(1+G_T/G_{\sigma y}) \end{aligned} \quad 4\text{-}2$$

expressed in decibels. It is important to recognize that since typically $\sigma_y^2 = \sigma_x^2/K^2(\phi) << \sigma_x^2$ or equivalently $G_{\sigma y} = G_{\sigma x}K^2(\phi) >> G_{\sigma x}$, where $K^2(\phi) = 1+224\sin^2(\phi)$ with ϕ being the signal penetration angle through the scattering volume, the antenna scattering loss will be dominated by the first term of (4-2). In Table 4-1 we have illustrated the antenna scattering loss as it depends on the various terminal sizes.

5. UPLINK AND DOWNLINK FADING

With respect to simultaneous uplink and downlink fading using a transponder satellite the resulting signal fading characteristics may be viewed as "the product" of two Rayleigh fading variables resulting in the Bessel type received power or signal amplitude probability distributions. This model assumes that the downlink is received by a terminal that it thermal

Table 4-1 Terminal Antenna Scattering Loss Illustrative Example.

Penetration Angle: Φ = 27.9 Degrees, [$K^2(\Phi)$ = 15 dB.]
Equivalent Antenna Gains: $G_{\sigma x}$ = 40 dB, $G_{\sigma y}$ = 55 dB.

Terminal Antenna Gain	(Size at 7/8 GHz)	Terminal Antenna Scattering Loss
G_T = 62 dB	(60')	L_s = 11.0+3.9 = 14.9 dB
= 58	(40')	= 9.0+2.4 = 11.4
= 52	(20')	= 6.1+0.9 = 7.0
= 44	(8')	= 2.7+0.2 = 2.9
= 35	(33")	= 0.6+0.0 = 0.6

front-end noise limited. That is by a small, low gain, earth terminal. Now if the signal is received by a large earth terminal for which the thermal front-end "noise floor" is insignificant relative to the noise level established by all other signals, the multiple access or interference signals, received from the satellite this noise level will also experience the same downlink fading as the desired signal. This implies that the effective received signal-to-noise ratio will not vary due to downlink fading and generally the automatic gain control (AGC) in the receiver will maintain an almost constant detection signal level with respect to downlink fading. However, downlink fading will result in phase modulation which can not be removed by the AGC and therefore downlink fading will affect the receiver demodulation performance.

Even if the receiver performance degradation from phase variations alone does not lend itself to analytical solutions we may be justified by using the small terminal model to bound the problem while we recognize that we need not account for antenna scattering loss for the downlink as long as the receive terminal noise level is set by the "other" received signals from the satellite. We know that the average fade rate is about $1/3\tau_o$ and thus the "deep" fades are separated in average by $\Delta t = 3\tau_o$ for which the normalized signal autocorrelation function $R(\Delta t) = \exp[-(\Delta t/\tau_o)^2] \approx 1\times10^{-4}$. In other words, the signal is virtually uncorrelated within a fraction of the average fade separation in time. Thus, we may attribute the signal decorrelation to the random phase process associated with the fading process and base the modulation subsystem designs not only on Rayleigh signal fading but on the Bessel type fading as well.

6. SYSTEMS ENGINEERING IMPLICATIONS

More importantly than the actual expressions for the signal decorrelation time (τ_o), coherent bandwidth (f_o) and the terminal antenna scattering loss (L_s) is the fact that these characteristics are all governed by the angular scattering distribution and in particular the angular scattering variances σ_x^2 and σ_y^2, or equivalently the equivalent antenna gains $G_{\sigma x}$ and $G_{\sigma y}$. This implies that as the angular scattering distribution changes over time the three characteristics also change together in time. Specifically, the minimum correlation time (fast signal fading), the minimum coherent bandwidth and the maximum antenna scattering loss are tied together and when we experience long signal decorrelation times (slow signal fading) the coherent bandwidth

is generally extremely large and the antenna scattering loss is negligible.

The question often raised is: how is it possible to mitigate against nuclear induced signal scintillations that will cause Rayleigh fading and associated signal decorrelation time and coherent bandwidth limitations? First, it is necessary not to employ a larger instantaneous transmission bandwidth than the minimum channel coherent bandwidth for an ECCM modulation subsystem whenever the digital transmission rates are comparable and lower than the maximum received signal fade rate. However, the total transmission bandwidth, or spread spectrum modulation bandwidth, may be made much larger than the coherent bandwidth by using frequency hopping since the bandwidth associated with each hop is the instantaneous bandwidth of the signal and much smaller. At the receiver it is necessary to restrict the demodulation coherence (integration) time to a value comparable or less than the minimum signal decorrelation time. This constraint still allows for non-coherent combining of many signal elements (chips) corresponding to a bit or transmission symbol.

7. REFERENCES

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